C & EE 141

Bolted Connections

Important Sections to Read

- AISC 360-10 Specification Chapter J.3
- AISC 360-10 Commentary Chapter J.3
- Part 7 of AISC SCM
- Textbook Chapter 10

Bolted Connections

- **EXTREMELY IMPORTANT TOPIC!!!!**
  - Inadequate connection design is the cause of many structural failures
  - I-35W Bridge 2007

- East Coast vs. West Coast
  - East: Connection design delegated to steel detailer
  - West: Connection design by S.E. for structure

Why Use Bolted Connections?

- Very Cost Effective
  - Less skilled labor required than welding
  - Reduced erection time versus welding
  - Simple to learn installation procedure

Types of Bolts

- Unfinished Bolts
  - ASTM A307
  - Similar steel properties to A36 steel
  - Used for light/secondary structures with static loads
  - Also known as “machine bolts”

Types of Bolts

- High-Strength Bolts
  - ASTM A325: Heat-treated medium carbon steel
  - ASTM A490: Heat-treated alloy steel
  - Higher strength than unfinished bolts
  - Used for primary structure
  - Don't become loose over time from vibration

Design Strength of Fasteners

Concept of High Strength Bolts

- Subject the bolt to a high tensile force by tightening the nut
- Tension force puts an equal compression force on the connected parts
- Shear resistance can be provided by the bolt via the tension force and the coefficient of friction at the faying surfaces
- Once the applied shear force exceeds the slip resistance, the bolt relies on shear of the bolt shaft and bearing resistance

Amount of Tensioning Required?

- Snug Tight
- Full Pretension
- Slip Critical

Snug Tight
(Not Pretensioned)

- Use when slip-resistance not required or when bolts are not subject to direct tension
- Typical “gravity” framing connections
- Installation method
  - Defined as “when all plies in a joint are in firm contact”
  - Few impacts of torque wrench or full effort of one man using an ordinary spud wrench

Pretensioned

- Pretensioned (70% of bolt ultimate tensile capacity)
  - Table J3.1
  - Used for connections with load reversal (seismic)
  - Used for connections subject to tensile fatigue
- Installation Methods
  - Turn-of-the-nut tightening
  - Calibrated torque wrench tightening
  - Direct tension indicator
  - “Twist-off” bolts

Slip Critical

- Slip-Critical Joints (fully pretensioned)
  - Required for connections involving shear or combined shear and tension (with load reversal)
- Special preparation of faying surfaces between connected parts
- Installation Methods
  - Same as pretensioned

Minimum Bolt Pretension

TABLE J3.1
Minimum Bolt Pretension, kips*

Bolt Size, in.	Group A (e.g., A325 Bolts)	Group B (e.g., A490 Bolts)
1/2	12	15
5/8	19	24
3/4	28	35
7/8	39	49
1	51	64
1 1/8	56	80
1 1/4	71	102
1 3/8	85	121
1 1/2	103	148

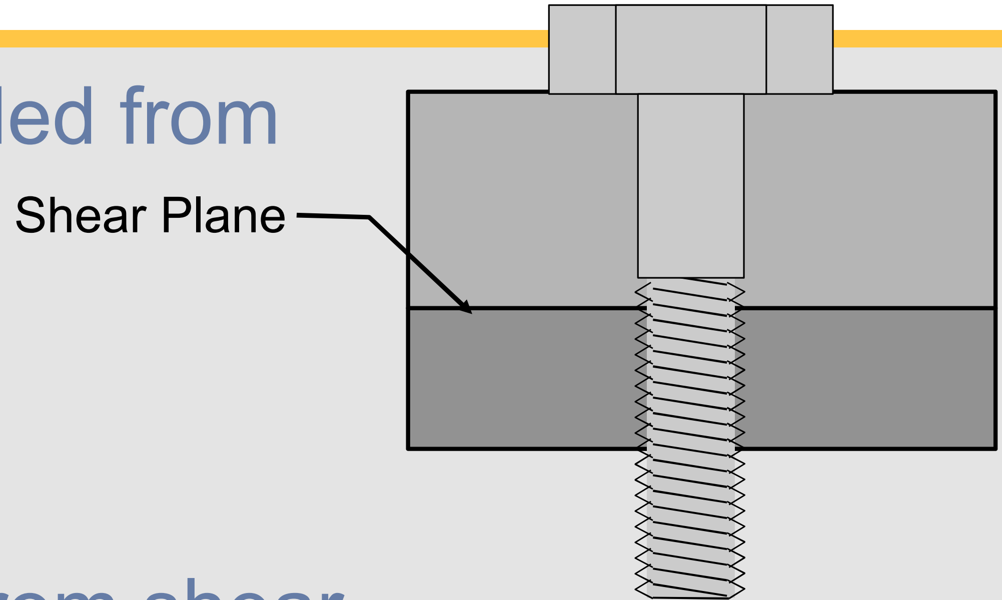
*Equal to 0.70 times the minimum tensile strength of bolts, rounded off to nearest kip, as specified in ASTM specifications for A325 and A490 bolts with UNC threads.

Common High Strength Bolt Designations

- A325-N & A490-N
  - Snug tight or bearing bolts with threads included (***N***ot excluded) in the shear plane
- A325-X & A490-X
  - Snug tight or bearing bolts with threads e***X***cluded from the shear plane
- A325-SC & A490-SC
  - Slip-critical bolts

–N and –X Designations

- –N: Threads ***N***ot excluded from shear plane



- –X: Threads e***X***cluded from shear plane

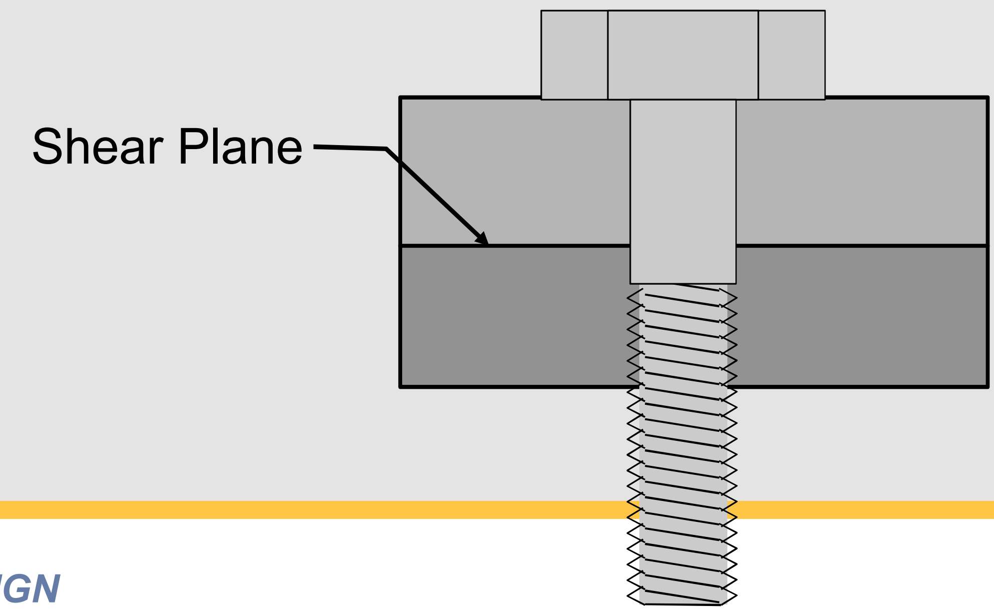


TABLE J3.2
Nominal Strength of Fasteners and Threaded Parts, ksi (MPa)

Description of Fasteners	Nominal Tensile Strength, F_{nt}, ksi (MPa)[a]	Nominal Shear Strength in Bearing-Type Connections, F_{nv}, ksi (MPa)[b]
A307 bolts	45 (310)	27 (188)[c] [d]
Group A (e.g., A325) bolts, when threads are not excluded from shear planes	90 (620)	54 (372)
Group A (e.g., A325) bolts, when threads are excluded from shear planes	90 (620)	68 (457)
Group B (e.g., A490) bolts, when threads are not excluded from shear planes	113 (780)	68 (457)
Group B (e.g., A490) bolts, when threads are excluded from shear planes	113 (780)	84 (579)
Threaded parts meeting the requirements of Section A3.4, when threads are not excluded from shear planes	$0.75F_u$	$0.450F_u$
Threaded parts meeting the requirements of Section A3.4, when threads are excluded from shear planes	$0.75F_u$	$0.563F_u$

[a] For high-strength bolts subject to tensile fatigue loading, see Appendix 3.
[b] For end loaded connections with a fastener pattern length greater than 38 in. (965 mm), F_{nv} shall be reduced to 83.3% of the tabulated values. Fastener pattern length is the maximum distance parallel to the line of force between the centerline of the bolts connecting two parts with one faying surface.
[c] For A307 bolts the tabulated values shall be reduced by 1% for each 1/16 in. (2 mm) over 5 diameters of length in the grip.
[d] Threads permitted in shear planes.

TABLE J3.2
Nominal Strength of Fasteners and Threaded Parts, ksi (MPa)

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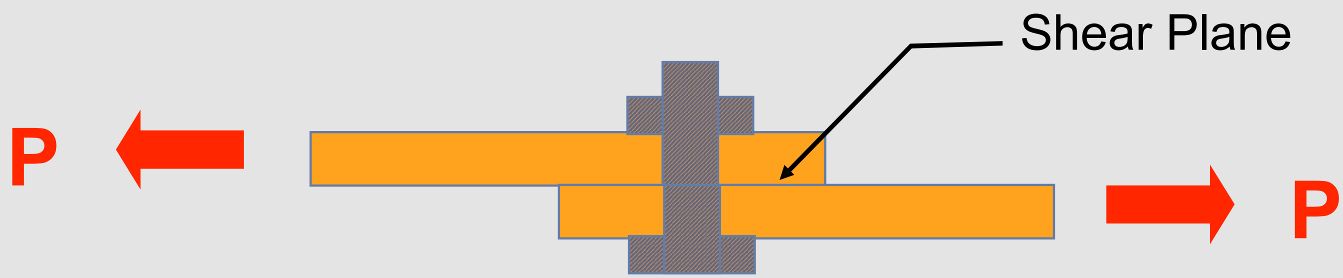
Group B (e.g., A490) bolts, when threads are not excluded from shear planes	113 (780)	68 (457)
Group B (e.g., A490) bolts, when threads are excluded from shear planes	113 (780)	84 (579)

Connection Types

- Simple Bolted Connections
  - Line of action of the forces coincidental with the "center of gravity" (workpoint) of the bolt group
- Eccentric Bolted Connections
  - Line of action of the forces <u>not</u> coincidental with the "center of gravity" (workpoint) of the bolt group
  - Subject of later lecture

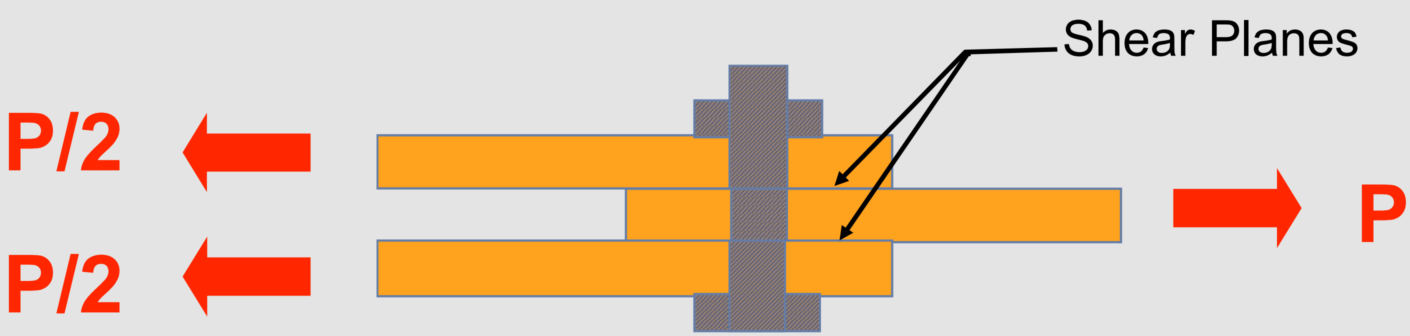
Joint Types

- Lap Joint (bolts in **single shear**)



$$f_v = \frac{P}{A_{bolts}}$$

- Butt Joint (bolts in **double shear**)



$$f_v = \frac{P}{2 * A_{bolts}}$$

Failure of Bolted Joints

- Shear failure of bolts (a & e)
- Tensile failure of the net section (b)
- Bearing failure of bolts and/or member (c)
- Shear failure of member due to insufficient “end distance” (d)
- Block shear (not shown)

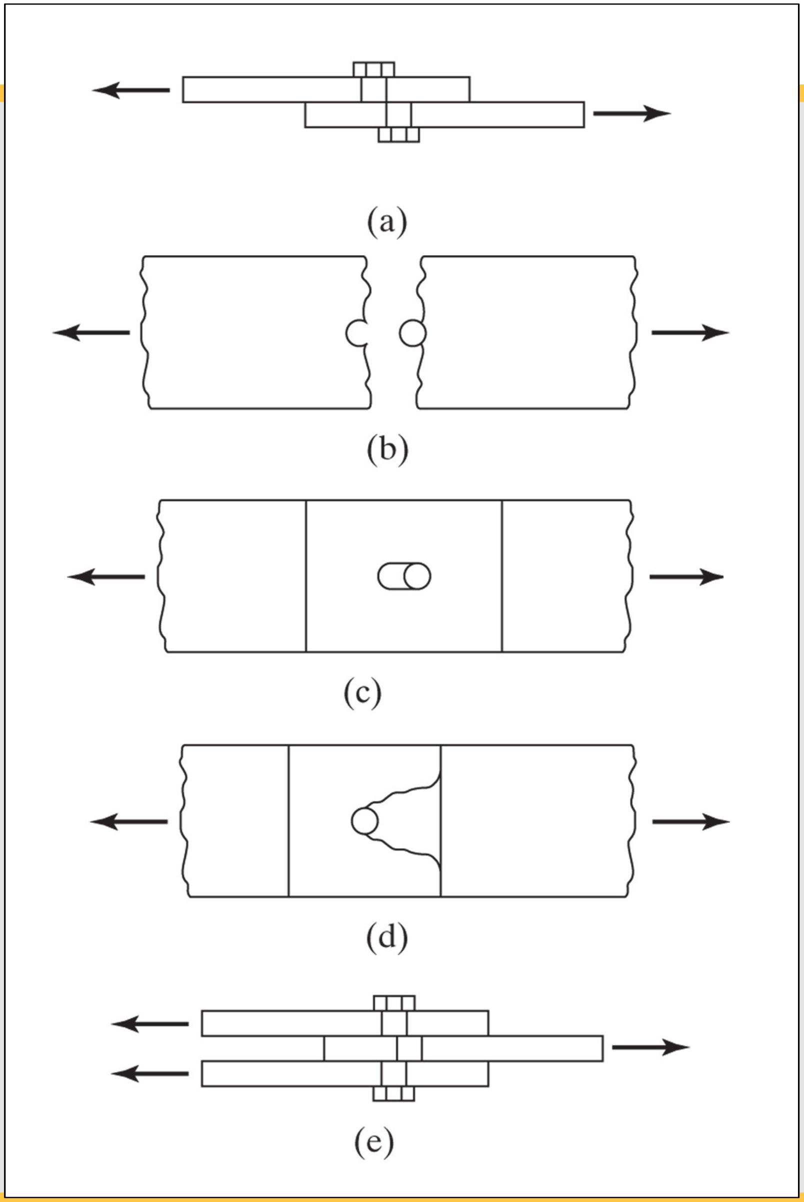
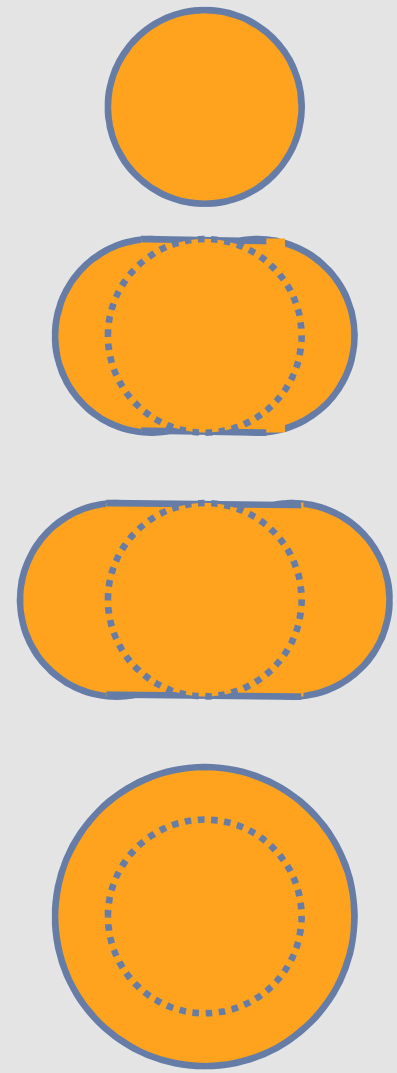


Figure 12.3 (a) Failure by single shearing of bolt. (b) Tension failure of plate. (c) Crushing failure of plate. (d) Shear failure of plate behind bolt. (e) Double shear failure of a butt joint.

Size and Use of Holes

- Standard Holes
  - 1/16” oversized
- Short-Slotted Holes
  - 1/16” oversized in one direction and slot perpendicular to direction of loading for bearing connections
  - Slot orientation not limited for slip-critical connections
- Long-Slotted Holes
  - 1/16” oversized in one direction and slot perpendicular to direction of loading for bearing connections
  - Slot orientation not limited for slip-critical connections
- Over-Sized Holes
  - Larger than 1/16” oversized all around bolt
  - Do not use in bearing connections



Size and Use of Holes

	TABLE J3.3 Nominal Hole Dimensions, in.			
	Hole Dimensions			
Bolt Diameter, in.	Standard (Dia.)	Oversize (Dia.)	Short-Slot (Width × Length)	Long-Slot (Width × Length)
$1/2$	$9/16$	$5/8$	$9/16 \times 11/16$	$9/16 \times 1\,1/4$
$5/8$	$11/16$	$13/16$	$11/16 \times 7/8$	$11/16 \times 1\,9/16$
$3/4$	$13/16$	$15/16$	$13/16 \times 1$	$13/16 \times 1\,7/8$
$7/8$	$15/16$	$1\,1/16$	$15/16 \times 1\,1/8$	$15/16 \times 2\,3/16$
1	$1\,1/16$	$1\,1/4$	$1\,1/16 \times 1\,5/16$	$1\,1/16 \times 2\frac{1}{2}$
$\geq 1\,1/8$	$d + 1/16$	$d + 5/16$	$(d + 1/16) \times (d + 3/8)$	$(d + 1/16) \times (2.5 \times d)$

Spacing & Edge Distance

- Minimum Spacing
  - 2.67 times the fastener diameter minimum
  - 3 times the fastener diameter preferred
- Minimum Edge Distance
  - Table J3.4 (safe to assume always a sheared edge)

- Maximum Spacing
  - 24 times thickness of thinner plate or 12” max
- Maximum Edge Distance
  - 12 times thickness of connected part or 6” max

Minimum Spacing and Edge Distance

TABLE J3.4
Minimum Edge Distance[a] from Center of Standard Hole[b] to Edge of Connected Part, in.

Bolt Diameter, in.	Minimum Edge Distance
1/2	3/4
5/8	7/8
3/4	1
7/8	1 1/8
1	1 1/4
1 1/8	1 1/2
1 1/4	1 5/8
Over 1 1/4	1 1/4 × d

[a] If necessary, lesser edge distances are permitted provided the appropriate provisions from Sections J3.10 and J4 are satisfied, but edge distances less than one bolt diameter are not permitted without approval from the engineer of record.
[b] For oversized or slotted holes, see Table J3.5.

Tension or Shear Strength of Bolts

$$Rn = F_n(\#\ \text{bolts})A_{bolt}$$

- Applicable to snug-tight or pretensioned
- Section J3.6, Eq J3-1 where $\Phi = 0.75$
- F_{nt} = Nominal tensile strength per Table J3.2
  - A307 = 45 ksi
  - A325 = 90 ksi (threads), 90 ksi (no threads)
  - A490 = 113 ksi (threads), 113 ksi (no threads)
- F_{nv} = Nominal shear strength per Table J3.2
  - A307 = 24 ksi
  - A325 = 48 ksi (threads), 60 ksi (no threads)
  - A490 = 60 ksi (threads), 75 ksi (no threads)

Combined Tension and Shear Strength of Bolts

$$Rn = F'_{nt}(\#\ \text{bolts})A_{bolt}$$

- Applicable to snug-tight or pretensioned (bearing connections)
- Section J3.7, Eq J3-2 where $\Phi = 0.75$
- $F'_{nt} = 1.3F_{nt} - (F_{nt}/\varphi F_{nv})\, f_{rv} \leq F_{nt}$ (J3-3a for LRFD)
- f_{rv} = required shear stress
- When the required stress in shear or tension is less than or equal to 30% of the corresponding available stress, the effects of combined stress need not be investigated.

Resistance of Slip-Critical Connections

$$Rn=\mu D_u h_f T_b n_s$$

- Applicable to fully pretensioned connections with prepared faying surfaces; still must check strength according to J3.6 and J3.7
- Section J3.8, Eq J3-4 where
  - Φ = 1.00 for standard and short-slotted holes perpendicular to direction of load
  - Φ = 0.85 for oversized and short-slotted holes parallel to direction of load
  - Φ = 0.70 for long-slotted
- μ = mean slip coefficient for Class A or B surfaces
  - 0.30 for Class A (unpainted clean mill scale steel…)
  - 0.50 for Class B (unpainted blast cleaned steel…)
- D_u = 1.13 ratio of specified to average bolt pretension
- h_f = factor for fillers
  - 1.00 for no filler plates or 1 filler plate
  - 0.85 for multiple filler plates
- T_b = minimum fastener tension per Table J3.1
- n_s = number of slip planes (shear planes)

Combined Tension and Shear in Slip-Critical Connections

- The applied tension reduces the net clamping force
- See Section J3.9
- Multiply the slip resistance of each bolt by:
  - $k_{sc} = 1 – (T_u/D_u T_b n_b)$ Eq J3-5a for LRFD
    - T_u = required tension force using LRFD
    - n_b = number of bolts carrying applied tension

Bearing Strength at Bolt Holes

- Section J3.10 where $\Phi = 0.75$
- For most types of holes (except as noted below):
  - When deformation at the bolt hole at *service load* is a design consideration:
    - $R_n = 1.2\ l_c t F_u \leq 2.4\ d t F_u$
  - When deformation at the bolt hole at *service load* is not a design consideration:
    - $R_n = 1.5\ l_c t F_u \leq 3.0\ d t F_u$
- For long-slotted holes with the slot perpendicular to the direction of force:
  - $R_n = 1.0\ l_c t F_u \leq 2.0\ d t F_u$

Bearing Strength at Bolt Holes

- Where:
  - d = nominal bolt diameter
  - F_u = specified minimum tensile strength of the connected material
  - l_c = clear distance, in the direction of force, between the edge of the hole and the edge of the adjacent hole or edge of the material
  - t = thickness of the connected material

Part 7: Design Tables

Table 7-1

Available Shear Strength of Bolts, kips

Nominal Bolt Diameter, d, in.					$^5/_8$		$^3/_4$		$^7/_8$		1	
Nominal Bolt Area, in.^{2}					0.307		0.442		0.601		0.785	
ASTM Desig.	Thread Cond.	F_{nv}/Ω (ksi)	ϕF_{nv} (ksi)	Load-ing	r_n/Ω	ϕr_n	r_n/Ω	ϕr_n	r_n/Ω	ϕr_n	r_n/Ω	ϕr_n
		ASD	LRFD		ASD	LRFD	ASD	LRFD	ASD	LRFD	ASD	LRFD
Group A	N	27.0	40.5	S	8.29	12.4	11.9	17.9	16.2	24.3	21.2	31.8
				D	16.6	24.9	23.9	35.8	32.5	48.7	42.4	63.6
	X	34.0	51.0	S	10.4	15.7	15.0	22.5	20.4	30.7	26.7	40.0
				D	20.9	31.3	30.1	45.1	40.9	61.3	53.4	80.1
Group B	N	34.0	51.0	S	10.4	15.7	15.0	22.5	20.4	30.7	26.7	40.0
				D	20.9	31.3	30.1	45.1	40.9	61.3	53.4	80.1
	X	42.0	63.0	S	12.9	19.3	18.6	27.8	25.2	37.9	33.0	49.5
				D	25.8	38.7	37.1	55.7	50.5	75.7	65.9	98.9
A307	–	13.5	20.3	S	4.14	6.23	5.97	8.97	8.11	12.2	10.6	15.9
				D	8.29	12.5	11.9	17.9	16.2	24.4	21.2	31.9

Table 7-2
Available Tensile Strength of Bolts, kips

Nominal Bolt Diameter, d, in.			5/8		3/4		7/8		1	
Nominal Bolt Area, in.^{2}			0.307		0.442		0.601		0.785	
ASTM Desig.	F_{nt}/Ω (ksi)	ϕF_{nt} (ksi)	r_n/Ω	ϕr_n	r_n/Ω	ϕr_n	r_n/Ω	ϕr_n	r_n/Ω	ϕr_n
	ASD	LRFD	ASD	LRFD	ASD	LRFD	ASD	LRFD	ASD	LRFD
Group A	45.0	67.5	13.8	20.7	19.9	29.8	27.1	40.6	35.3	53.0
Group B	56.5	84.8	17.3	26.0	25.0	37.4	34.0	51.0	44.4	66.6
A307	22.5	33.8	6.90	10.4	9.94	14.9	13.5	20.3	17.7	26.5

Nominal Bolt Diameter, d, in.			1 1/8		1 1/4		1 3/8		1 1/2	
Nominal Bolt Area, in.^{2}			0.994		1.23		1.48		1.77	
ASTM Desig.	F_{nt}/Ω (ksi)	ϕF_{nt} (ksi)	r_n/Ω	ϕr_n	r_n/Ω	ϕr_n	r_n/Ω	ϕr_n	r_n/Ω	ϕr_n
	ASD	LRFD	ASD	LRFD	ASD	LRFD	ASD	LRFD	ASD	LRFD
Group A	45.0	67.5	44.7	67.1	55.2	82.8	66.8	100	79.5	119
Group B	56.5	84.8	56.2	84.2	69.3	104	83.9	126	99.8	150
A307	22.5	33.8	22.4	33.5	27.6	41.4	33.4	50.1	39.8	59.6

ASD	LRFD
$\Omega = 2.00$	$\phi = 0.75$

Group A Bolts

Table 7-3
Slip-Critical Connections
Available Shear Strength, kips
(Class A Faying Surface, μ = 0.30)

Group A Bolts									
Hole Type	Loading	Nominal Bolt Diameter, *d*, in.							
		5/8		3/4		7/8		1	
		Minimum Group A Bolt Pretension, kips							
		19		28		39		51	
		r_n/Ω	ϕr_n	r_n/Ω	ϕr_n	r_n/Ω	ϕr_n	r_n/Ω	ϕr_n
		ASD	LRFD	ASD	LRFD	ASD	LRFD	ASD	LRFD
STD/SSLT	S	4.29	6.44	6.33	9.49	8.81	13.2	11.5	17.3
	D	8.59	12.9	12.7	19.0	17.6	26.4	23.1	34.6
OVS/SSLP	S	3.66	5.47	5.39	8.07	7.51	11.2	9.82	14.7
	D	7.32	10.9	10.8	16.1	15.0	22.5	19.6	29.4
LSL	S	3.01	4.51	4.44	6.64	6.18	9.25	8.08	12.1
	D	6.02	9.02	8.87	13.3	12.4	18.5	16.2	24.2

Table 7-3 (continued)

Slip-Critical Connections

Available Shear Strength, kips

(Class A Faying Surface, $\mu = 0.30$)

Group B Bolts

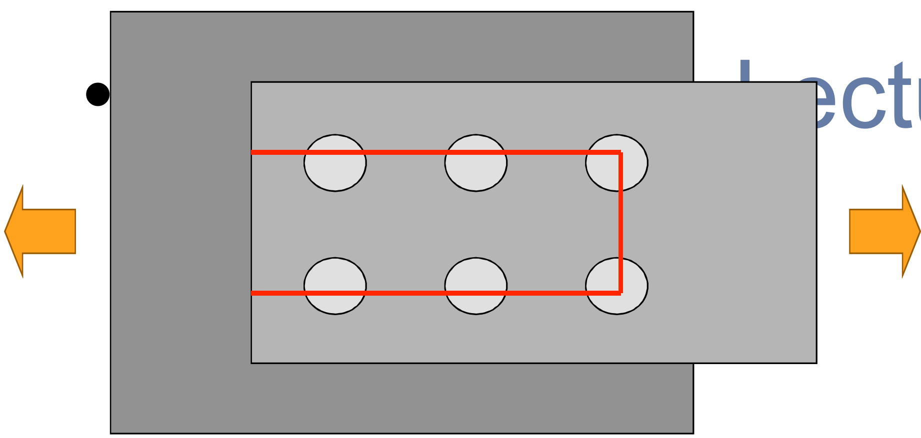
Group B Bolts									
Hole Type	Loading	Nominal Bolt Diameter, *d*, in.							
		5/8		3/4		7/8		1	
		Minimum Group B Bolt Pretension, kips							
		24		35		49		64	
		r_n/Ω	ϕr_n	r_n/Ω	ϕr_n	r_n/Ω	ϕr_n	r_n/Ω	ϕr_n
		ASD	LRFD	ASD	LRFD	ASD	LRFD	ASD	LRFD
STD/SSLT	S	5.42	8.14	7.91	11.9	11.1	16.6	14.5	21.7
	D	10.8	16.3	15.8	23.7	22.1	33.2	28.9	43.4
OVS/SSLP	S	4.62	6.92	6.74	10.1	9.44	14.1	12.3	18.4
	D	9.25	13.8	13.5	20.2	18.9	28.2	24.7	36.9
LSL	S	3.80	5.70	5.54	8.31	7.76	11.6	10.1	15.2
	D	7.60	11.4	11.1	16.6	15.5	23.3	20.3	30.4

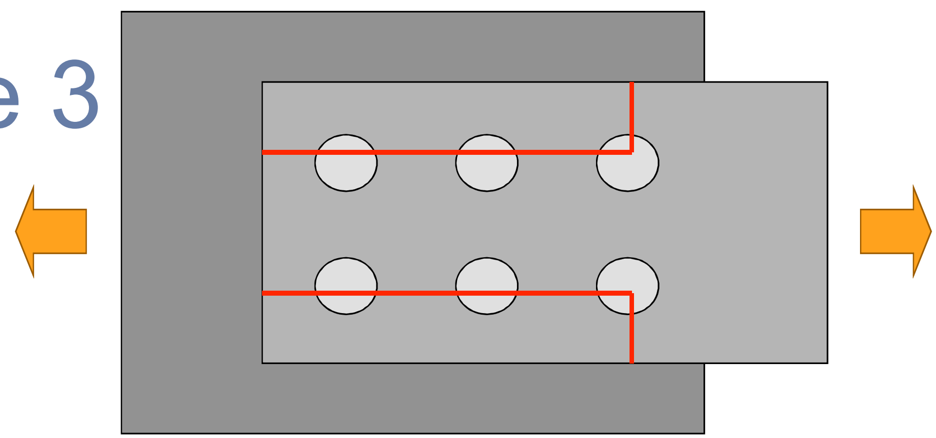
Recall: Block Shear

- Tearout of piece of steel in a connection from combination of tensile rupture and either shear rupture or shear yield

- Technically a connection limit state

- Lecture 3





Examples of Block Shear

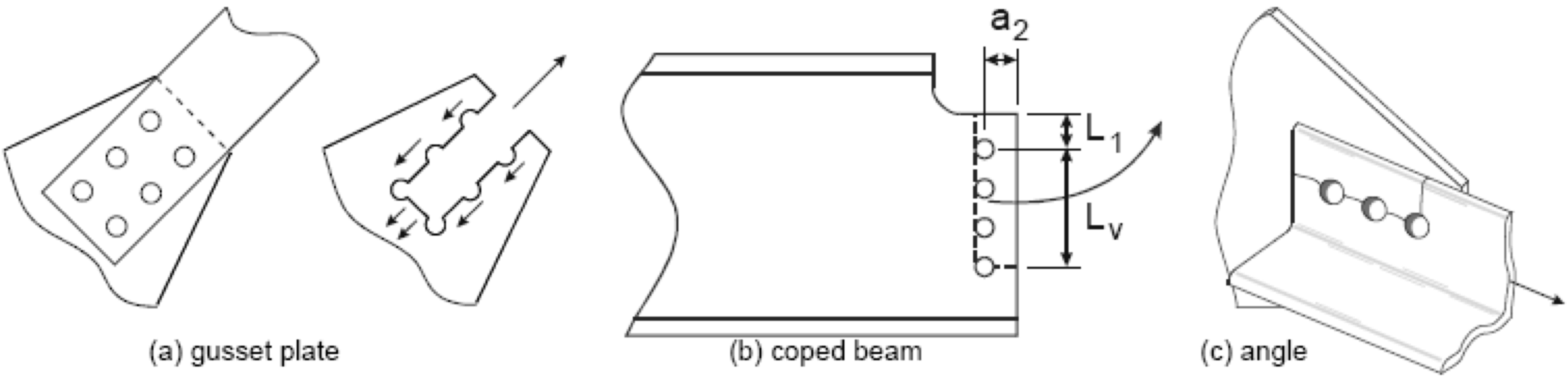
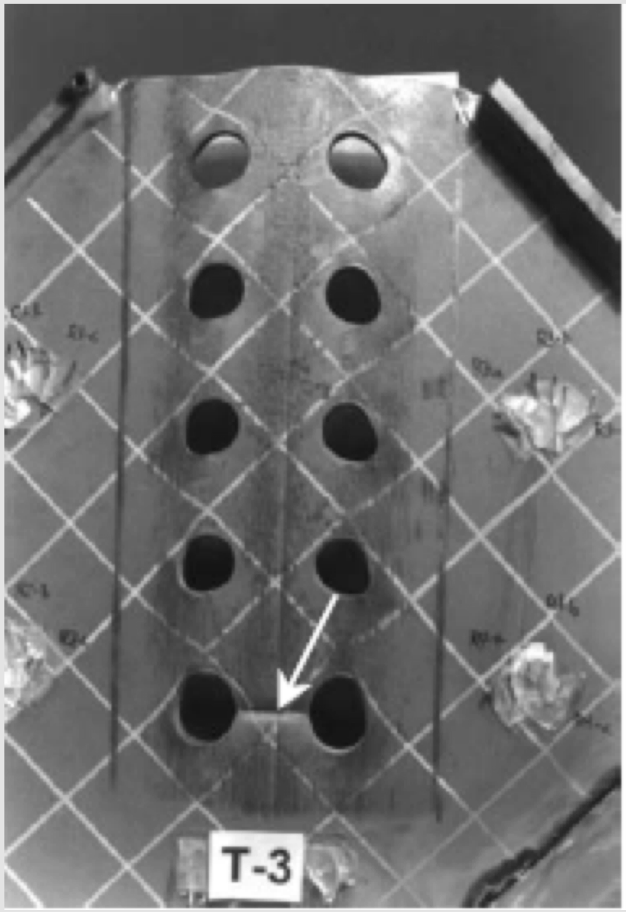


Figure 1 – Examples of Block Shear

Block Shear Failure Tests



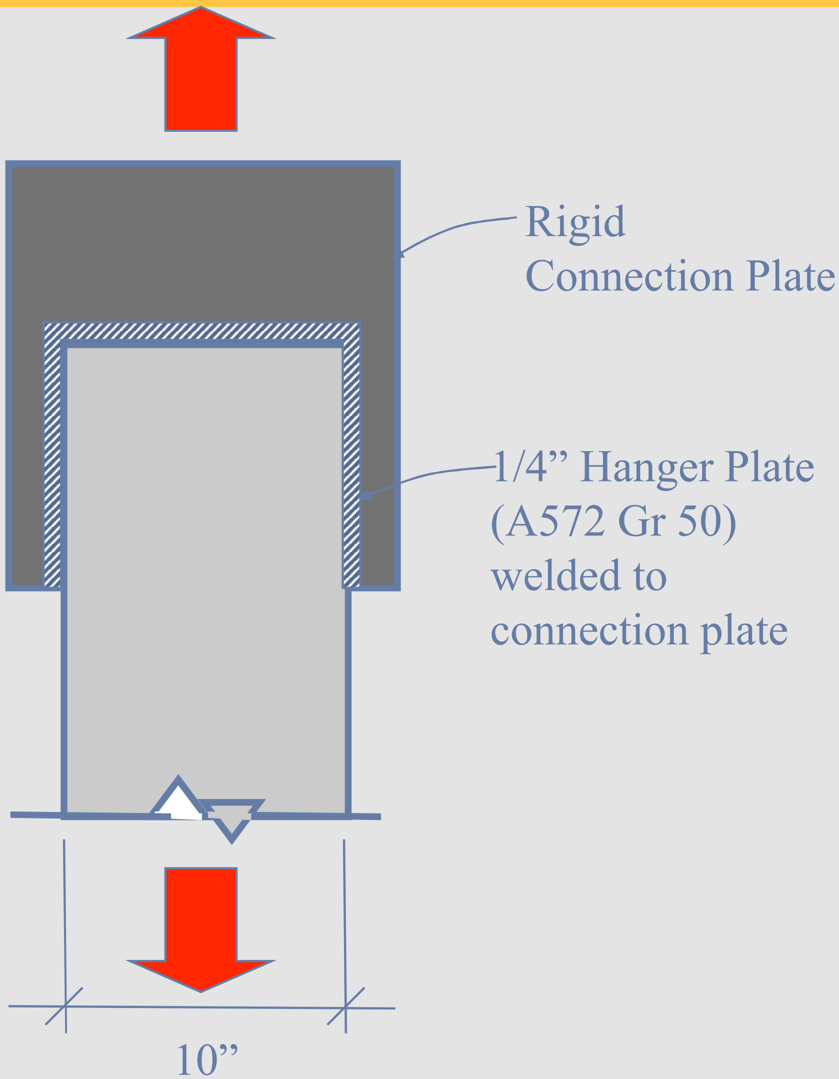
Questions?

Example Problem from Tension Members Lecture

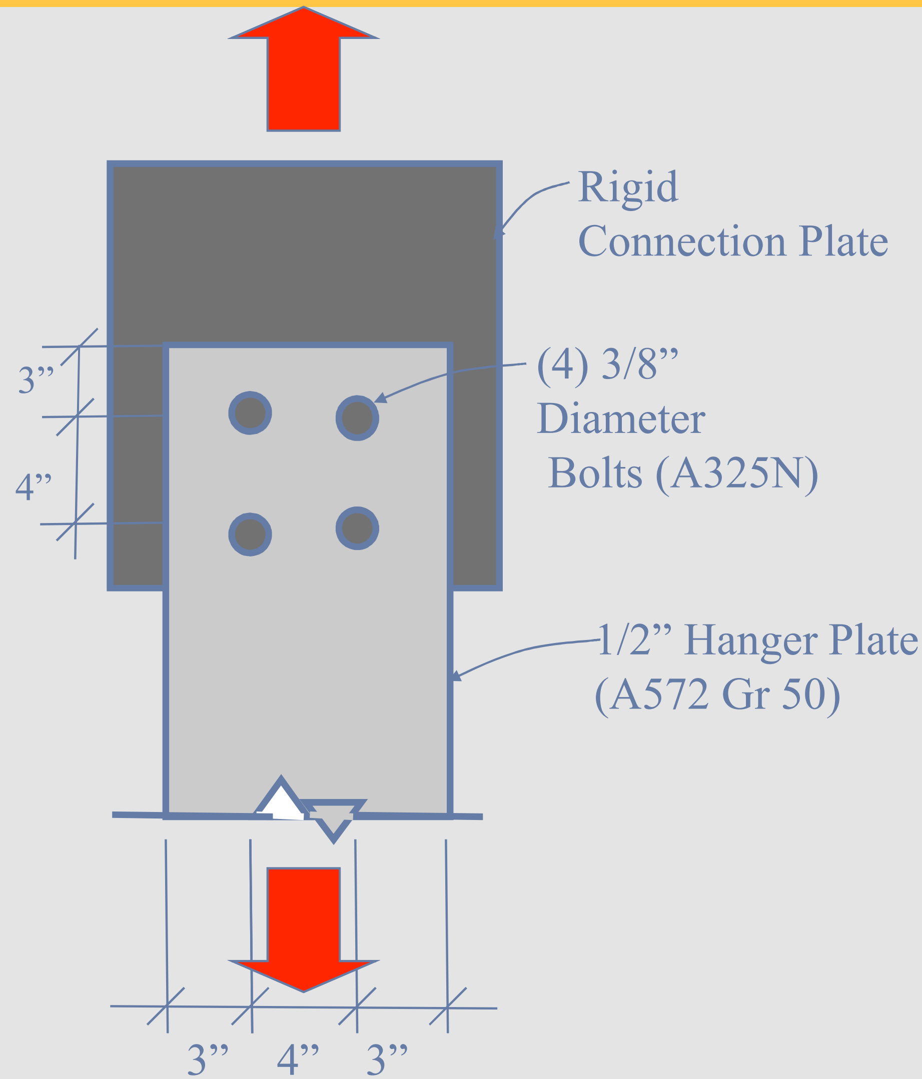
- You have designed a welded connection detail for the hanger plate shown in the figure labeled “Designed Detail”.
- You utilized a welded connection in order to develop the full tensile capacity of the plate.
- The contractor doesn’t want to weld the connection so he proposed a bolted connection shown in the figure labeled “Proposed Detail”.
- The contractor is aware that the bolts will decrease the capacity of the plate hanger so he proposes thickening the hanger plate as indicated.
- Will you approve of the bolted connection in lieu of the welded connection? Provide all necessary calculations to justify your response.

- WHAT ABOUT THE CAPACITY OF THE BOLTS?

Example Problem from Tension Members Lecture



Designed Detail



Proposed Detail

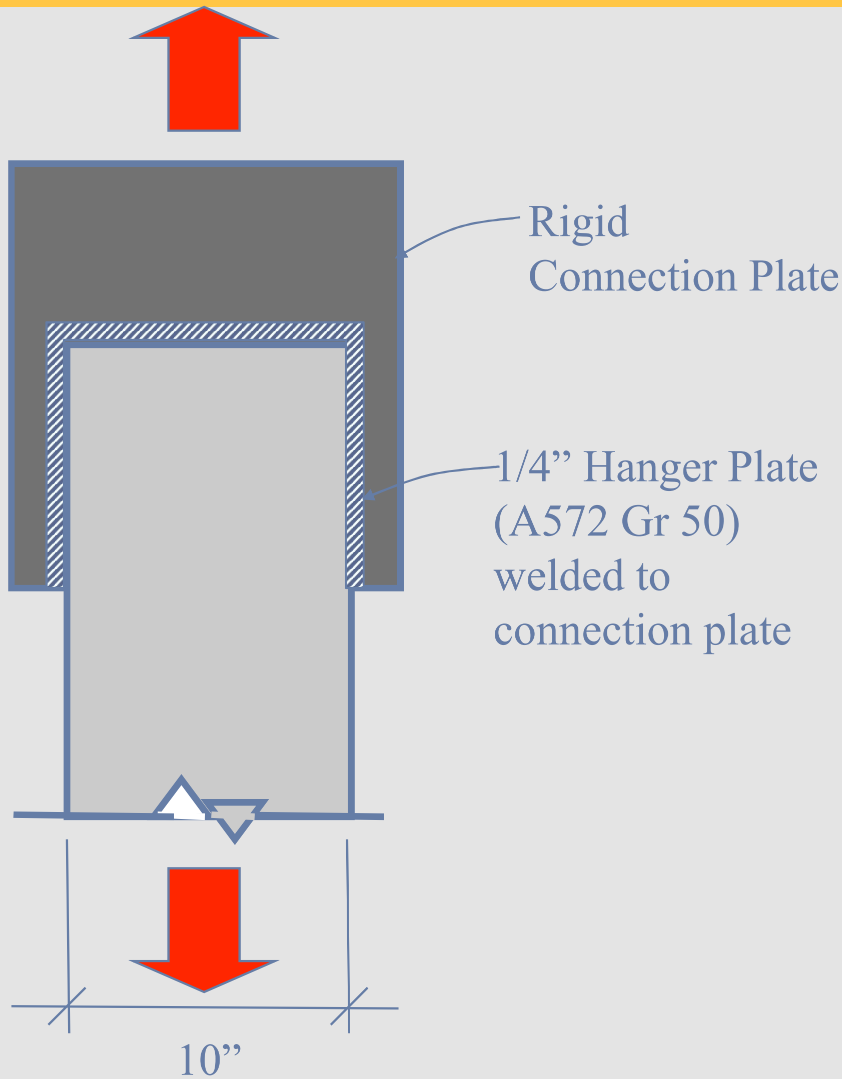
Example Problem from Tension Members Lecture

A572 Grade 50 Steel
Fy = 50 ksi
Fu = 65 ksi

Strength of Original Plate:

yielding: A_g = ¼” · 10” = 2.5 in^2

$\Phi P_n = \Phi F_y \cdot A_g$
= 0.9 · 50 ksi · 2.5 in^2
= **113 *kips***



Designed Detail

Example Problem from Tension Members Lecture

<u>*A572 Grade 50 Steel*</u>
Fy = 50 ksi
Fu = 65 ksi

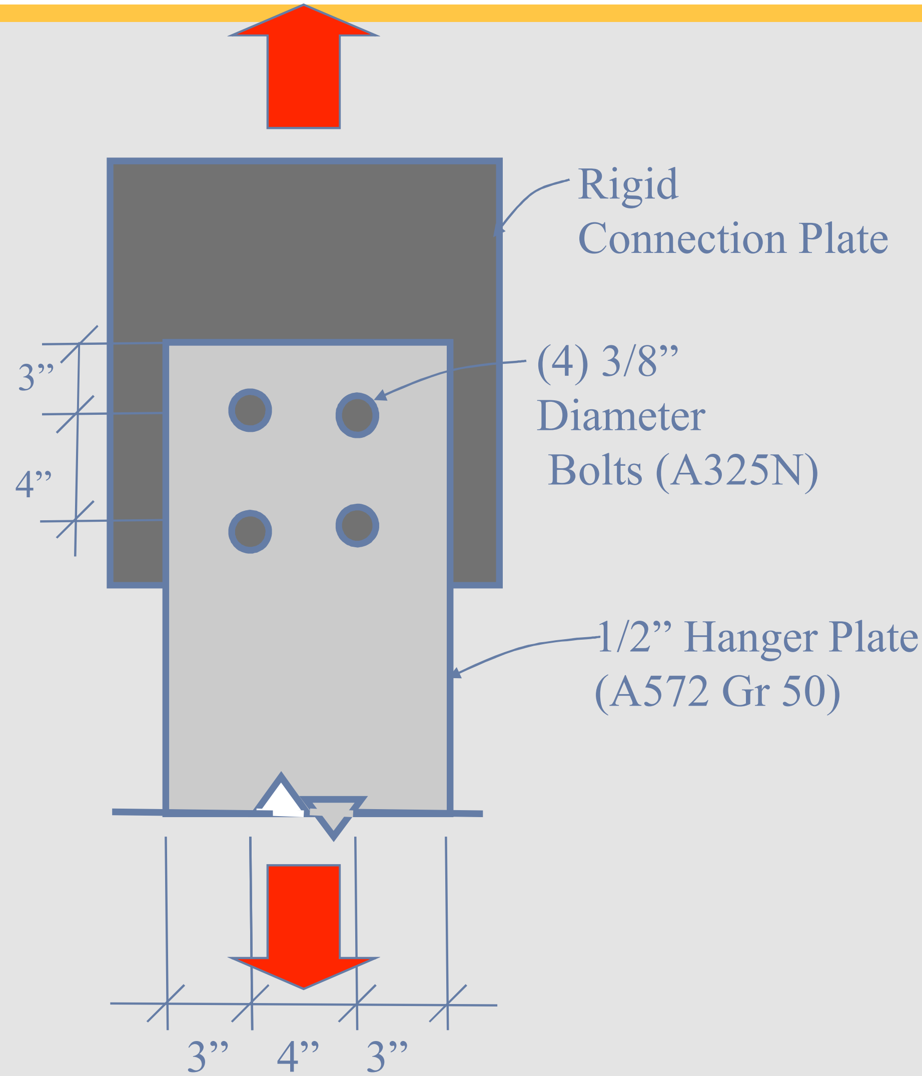
<u>Strength of Proposed Plate:</u>

1. yielding: $A_g = ½" \cdot 10" = 5.0\ in^2$

$$\Phi P_n = \Phi F_y \cdot A_g$$
$$= 0.9 \cdot 50 \text{ ksi} \cdot 5.0 \text{ in}^2$$
$$= 225\ kips$$

2. fracture: $An = (½")(10" – 2 \cdot (^3/_8" + ^1/_8"))$

$$= 4.5\ in^2$$
$$\Phi P_n = \Phi F_u \cdot A_n$$
$$= 0.75 \cdot 65 \text{ ksi} \cdot 4.5 \text{ in}^2$$
$$= 219\ kips$$



<u>Proposed Detail</u>

Example Problem from Tension Members Lecture

A572 Grade 50 Steel

Fy = 50 ksi

Fu = 65 ksi

Nominal Capacity:

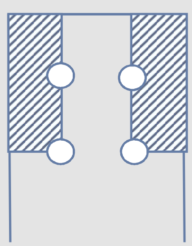
$R_n = 0.6\, F_u\, A_{nv} + U_{bs}\, F_u\, A_{nt}$

$= 0.6\, F_y\, A_{gv} + U_{bs}\, F_u\, A_{nt}$

- Use the lesser of the two equations

Strength of Proposed Plate:

3. Block shear:



A_{nt} = 2.75 in2

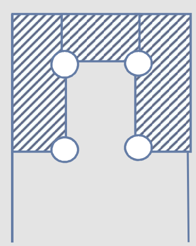
A_{nv} = 6.25 in2

A_{gv} = 7.0 in2

R_n = 423 kips

= 389 kips

ΦR_n = 292 kips



A_{nt} = 4.5 in2

A_{nv} = 3.5 in2

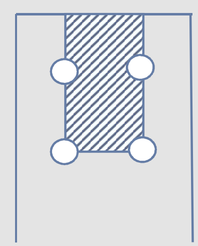
A_{gv} = 4.0 in2

R_n = 429 kips

= 413 kips

ΦR_n = 309 kips

GOVERNING CASE



A_{nt} = 1.75 in2

A_{nv} = 6.25 in2

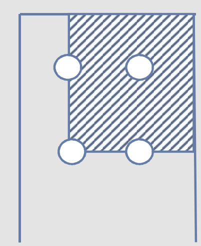
A_{gv} = 7.0 in2

R_n = 358 kips

= 324 kips

ΦR_n = 243 kips

NOT A REAL CASE



Example Problem from Tension Members Lecture

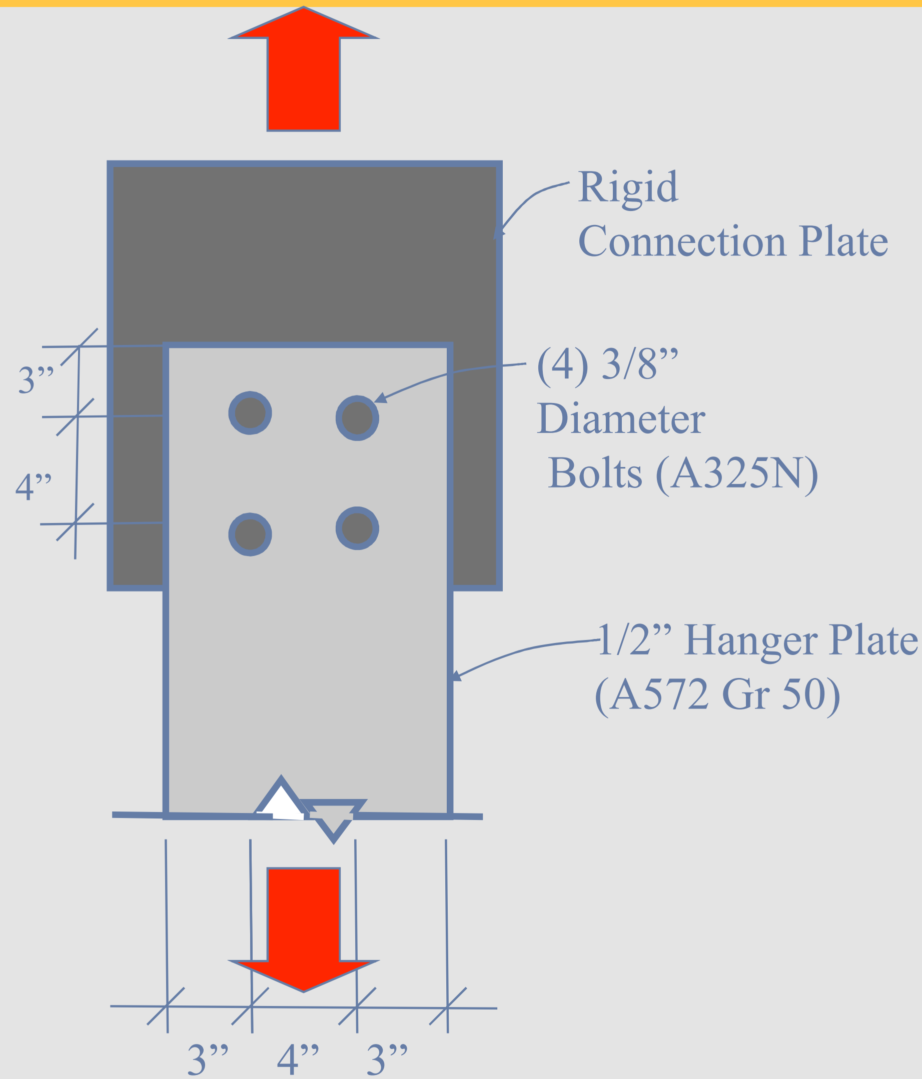
A572 Grade 50 Steel
Fy = 50 ksi
Fu = 65 ksi

Strength of Proposed Plate:

1. yielding: ΦP_n = 225 kips

2. fracture: ΦP_n = **219 kips**

3. Block shear: ΦP_n = 243 kips

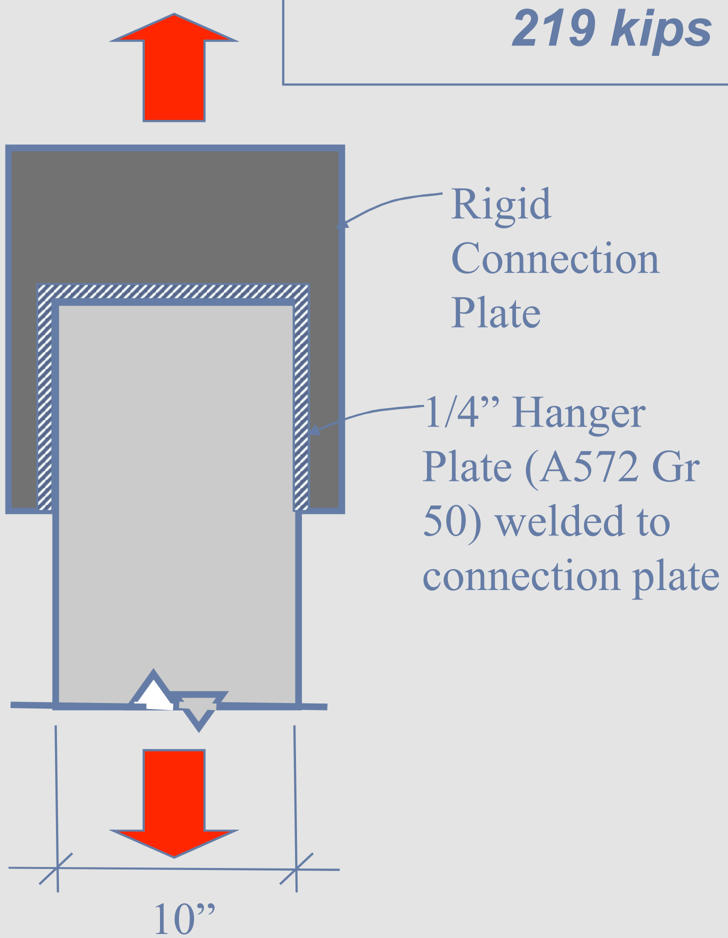


Proposed Detail

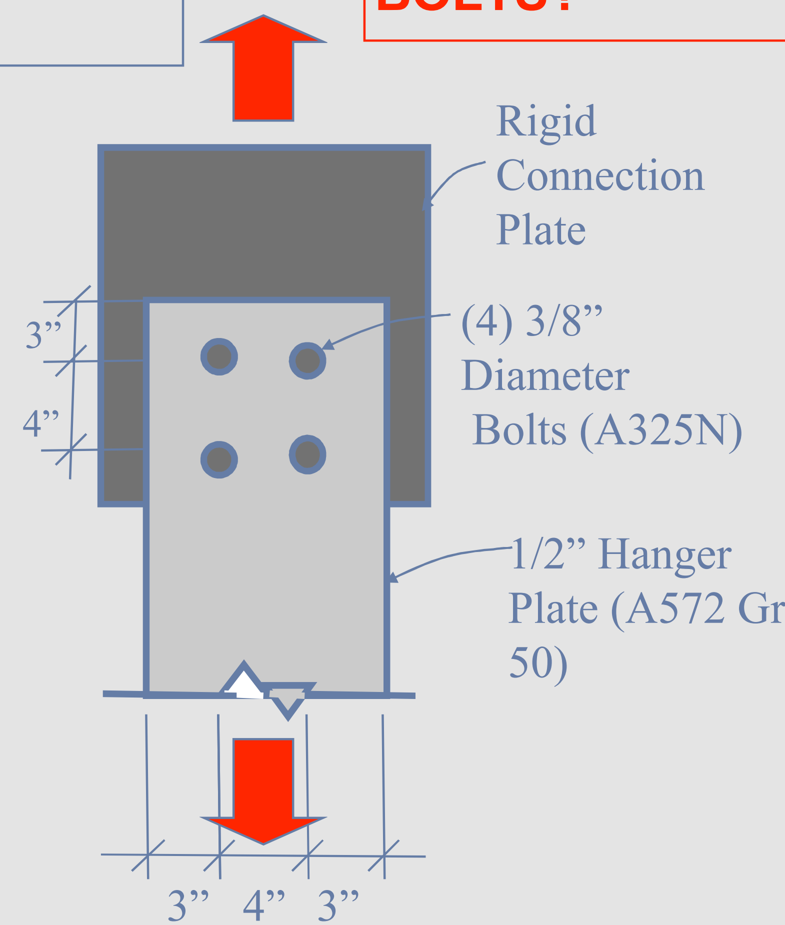
Example Problem from Tension Members Lecture

CONNECTION APPROVED SINCE
ΦP_n (proposed) > ΦP_n (original)
219 kips > 113 kips

WHAT ABOUT THE CAPACITY OF THE BOLTS?



Designed Detail



Proposed Detail

Example Problem Continued (Capacity of the Bolts)

(4) 3/8" dia A325-N Bolts

Bearing Capacity of Bolts

$\Phi R_n = \Phi 1.2\, l_c t F_u N_{bolts} \leq \Phi 2.4\, d t F_u N_{bolts}$

$= (0.75)1.2(3"-7/32")(0.5")(65ksi)(4)$

$= 325$ kips (conservative*)

$= (0.75)2.4(3/8")(0.5")(65ksi)(4)$

$= 88$ kips (*governs for bearing)*

Shear Capacity of Bolts

$\Phi P_n = \Phi F_n A_b N_{bolts}$

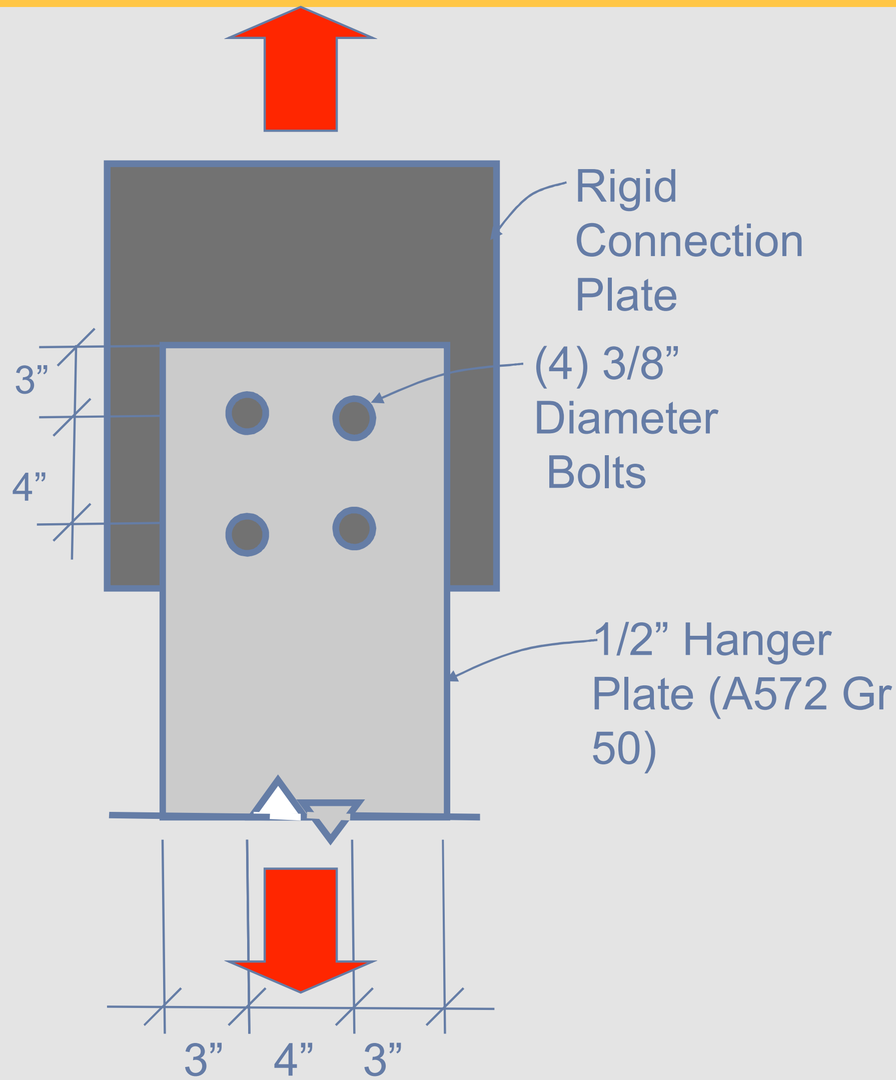
$= (0.75)(54ksi)(0.11in^2)(4)$

$= 17.8$ kips

Connection Capacity Limited by Bolts

$\Phi Pn = 17.8$ kips

DO NOT APPROVE THE CONNECTION



Proposed Detail